

S -wave pairing symmetry in non-centrosymmetric superconductor Re_3W

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Abstract

The alloys of non-centrosymmetric superconductor, Re_3W , which were reported to have an α -Mn structure [P. Greenfield and P. A. Beck, J. Metals, N. Y. **8**, 265 (1959)] with $T_c = 9$ K were prepared by arc melting. The ac susceptibility and low-temperature specific heat were measured on these alloys. It is found that there are two superconducting phases coexisting in the samples with $T_{c1} \sim 9$ K and $T_{c2} \sim 7$ K, both of which have a non-centrosymmetric structure as reported previously. By analyzing the specific heat data measured in various magnetic fields, we found that the absence of the inversion symmetry does not lead to the deviation from a s -wave pairing symmetry in Re_3W .

Key words: Re_3W , Non-centrosymmetric, Superconductivity, Specific heat

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1 Introduction

Very recently the scientific community has paid a lot of attention in understanding the superconductivity of the non-centrosymmetric superconductors, since the superconducting properties of such materials are expected to be unconventional [1,2,3,4,5,6,7]. In a lattice with inversion symmetry, the orbital wave function of the cooper pair has a certain symmetry and the spin paring will be simply in either the singlet or triplet state. The noncentrosymmetry in the lattice may bring a complexity to the symmetry of orbital wave function. This effect with the antisymmetric spin-orbital coupling gives rise to the broken of the spin degeneracy, thus the existence of the mixture of spin singlet and triplet may become possible[2,5]. So there might be something unconventional, such as spin triplet pairing component, existing in the non-centrosymmetric superconductors. Recently, a spin-triplet pairing component was demonstrated in $\text{Li}_2\text{Pt}_3\text{B}$ both by penetration depth measurement[4] and nuclear magnetic resonance (NMR)[5], as was ascribed to the large atomic number of Pt which enhances the spin-orbit coupling.

Re_3W is one of the rhenium and tungsten alloys' family. Up to now, two superconducting phases of Re_3W were reported with $T_c \sim 9 \text{ K}$ [8] and $T_c \sim 7\text{K}$ [9]. Both phases belong to the $\alpha\text{-Mn}$ phase (A12, space group $\bar{1}43m$)[10], which has a non-centrosymmetric structure. Moreover, atomic numbers of Re and W are 75 and 74, respectively, being close to that of Pt. Therefore, similar spin-triplet pairing component as that in $\text{Li}_2\text{Pt}_3\text{B}$ are expected in Re_3W . Most recently, it was found that the superconducting phase of Re_3W with $T_c \sim 7 \text{ K}$ is a weak-coupling s-wave BCS superconductor by both penetration depth [9] and Andreev reflection measurements [11].

In this paper, we report the measurements of the ac susceptibility and low-temperature specific heat of Re_3W alloys. Both the measurements imply that our samples have two superconducting phases with critical temperatures near 9 K and 7 K, respectively, and the high temperature phase near 9 K accounts for nearly 78%-87% in total volume. The specific heat data can be fitted very well by the simple two-component model, which is based on the isotropic s-wave BSC theory. Furthermore, a linear relationship is found between the zero-temperature electronic specific heat coefficient and the applied magnetic field. These results suggest that the absence of the inversion symmetry does not result in novel pairing symmetry in Re_3W .

2 Experiment

The Re_3W alloys are prepared by arc melting the Re and W powders (purity of 99.9% for both) with nominal component 3 : 1 in a Ti-gettered argon atmosphere. Normally, the obtained alloy is a hemisphere in shape with a dimension of 5 mm (radius) \times 5 mm (height). Some pieces of the alloy had been cut from the original bulk (e.g. sample #1 and sample #2). The ac susceptibility of these samples has been measured at zero dc magnetic field to identify their superconducting phases, whereas, all of them have two superconducting transitions at about 9 K and 7 K, as shown in Fig. 1. The specific heat was measured by a Physical Property Measurement System (PPMS, Quantum Design). The data at a magnetic field were obtained with increasing temperature after being cooled in field from a temperature well above T_c , namely, field cooling process.

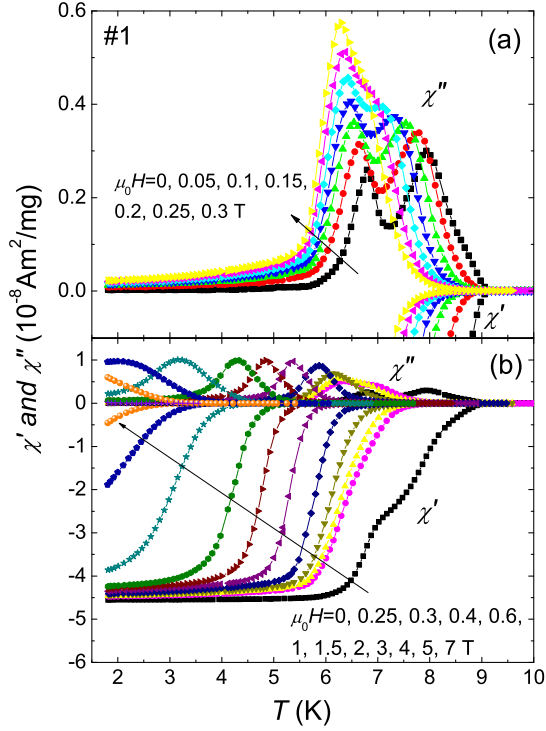


Fig. 1. (Color online) Temperature dependence of ac susceptibility on sample #1 under different dc magnetic fields, with ac field $h = 1$ Oe and frequency $f = 333$ Hz.

3 Results and discussion

The temperature dependence of ac susceptibility ($\chi = \chi' + i\chi''$) at different dc magnetic fields from 0 T to 7 T is shown in Fig. 1. One can see that two distinct superconducting transitions occur at $T_{c1} \sim 9$ and $T_{c2} \sim 7$ K in $\chi'(T)$ curve at $H = 0$ [Fig. 1(b)], and double peaks in $\chi''(T)$ show up at the corresponding temperatures. These two phases are consistent with the previous reports in which they are proofed to be non-centrosymmetric[8,9]. The peaks of χ'' shift to lower temperatures as the magnetic field increases, showing the continuous suppression of superconductivity by the magnetic field. The low- T peak shifts to lower temperatures more slowly than the high- T one, indicating distinct behaviors of the upper critical fields in these two superconducting phases. As

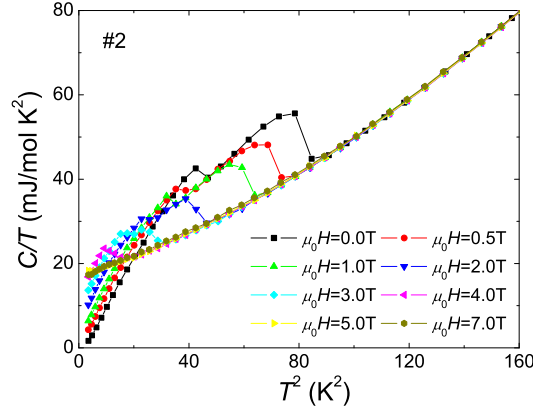


Fig. 2. (Color online) Specific heat data of sample #2 plotted as C/T versus T^2 at various fields.

H increases to ~ 7 T, the $\chi(T)$ curves are completely flat, showing no sign of superconducting transition. Similar results were obtained on sample #2 and other samples.

We thus measured the specific heat of sample #2 and in Fig. 2 we present the data of C/T versus T^2 at various magnetic fields. On each curve, there are two jumps related to the superconducting transitions consistent with the measurements of ac susceptibility. From the zero field data in low temperature region, one can see that the residual specific heat coefficient γ_0 is close to zero, implying the absence of non-superconducting phase. The superconducting anomaly is suppressed gradually with increasing magnetic field, and from the curve at 7 T there is no sign of superconductivity above 1.8 K, consistent with the observation in $\chi(T)$ curve. The low temperature part of the normal state specific heat at $H = 7$ T in Fig. 2 is not a straight line, implying that the specific heat of phonon does not satisfy the Debye's T^3 law. We may need a T^7 term to fit the normal state specific heat well:

$$C_n/T = \gamma_n + \beta_3 T^2 + \beta_5 T^4 + \beta_7 T^6. \quad (1)$$

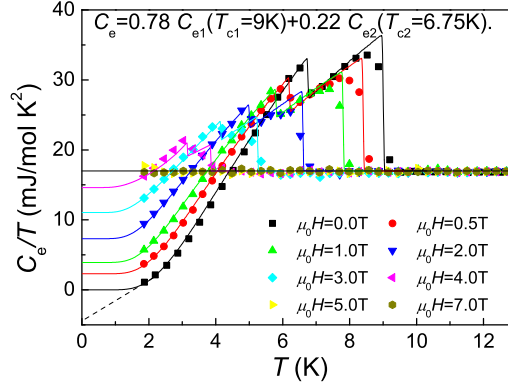


Fig. 3. (Color online) Specific heat of electrons plotted as C_e/T versus T . The solid lines are the calculating results which separate the electronic specific heat into two components with different T_c by using specific heat formula based on the BCS theory.

The first term is the electronic specific heat in the normal state, and the others are the contributions of the phonons. Fitting the data of 7 T to Eq. (1), the coefficients $\gamma_n = 17 \pm 0.1$ mJ/mol K², $\beta_3 = 0.185 \pm 0.001$ mJ/mol K⁴, $\beta_5 = (1.63 \pm 0.01) \times 10^{-3}$ mJ/mol K⁶, and $\beta_7 = (-2.087 \pm 0.005) \times 10^{-6}$ mJ/mol K⁸ are determined. From the relation:

$$\beta_3 = \frac{12\pi^4}{5} \frac{N_A k_B Z}{\Theta_D^3}, \quad (2)$$

where $N_A = 6.02 \times 10^{23}$ is the Avogadro constant, and $Z = 4$ the number of atoms in one unit cell, we obtained the Debye temperature of our alloys $\Theta_D = 347.9$ K. These coefficients and Debye temperature are all very close to the results of other works on Re-W alloys[12,13,14,15,16,17,18].

By subtracting the phonon contribution, the electronic specific heat C_e is obtained, which is shown in Fig. 3 as C_e/T versus T . Before a quantitative analysis, the low temperature specific heat at low fields has presented a strong

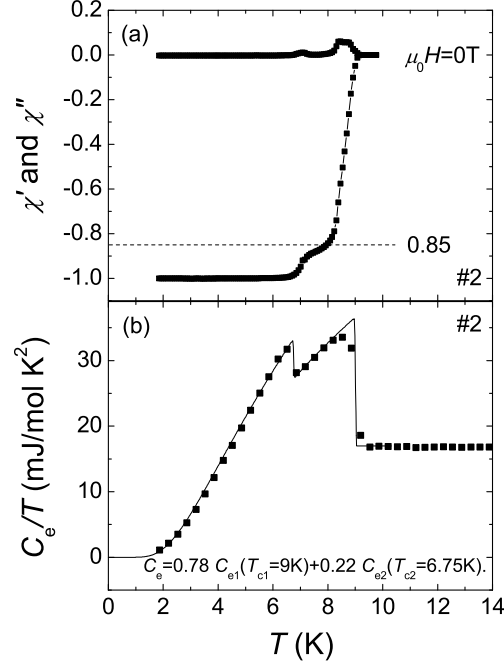


Fig. 4. (a) shows the ac susceptibility of sample #2 on which the specific heat have been measured. (b) shows the zero field specific heat data, and the black line is the calculating result based on the BCS theory.

evidence that Re_3W has a nodeless gap function. For a nodal superconductor (expected by the strong mixing of spin-singlet and spin-triplet pairing components in a heavily non-centrosymmetric superconductor such as $\text{Li}_2\text{Pt}_3\text{B}$), the low temperature C/T vs. T relation should be a power law like. However, as denoted by the dashed lines in Fig. 3, if a linear relationship is assumed, the specific heat at zero field would be negative when the temperature approaches to zero. In the following section, by using a quantitative analysis, we will demonstrate that both phases of Re_3W have an isotropic gap function, which is in good agreement with the expectation of an s -wave superconductor.

Figure 4 shows the ac susceptibility and specific heat data at zero dc field measured on the same sample(#2). The ac susceptibility data have been nor-

malized. The high temperature phase occupies nearly $85 \pm 1\%$ in the whole superconducting volume. In order to fit the zero field electronic specific heat, we attempt to use the formula derived from thermodynamic relations based on the BCS theory[19]

$$C_{\text{es}} = \frac{4N(0)}{k_{\text{B}}T^2} \int_0^\infty \frac{e^{\zeta/k_{\text{B}}T}}{(1 + e^{\zeta/k_{\text{B}}T})^2} (\varepsilon^2 + \Delta^2(T) - \frac{T}{2} \frac{d\Delta^2(T)}{dT}) d\varepsilon, \quad (3)$$

where $\zeta = \sqrt{\varepsilon^2 + \Delta^2(T)}$, and $\Delta(T)$ is an isotropic *s*-wave gap which depends on temperature in the same way as expected by BCS theory. Since there are two coexistent phases in our samples, we use two separate terms of C_H and C_L to take into account the contributions of the high T_c and low T_c phases, respectively. Thus the total specific heat can be expressed as follows:

$$C_e = \omega_H C_H + \omega_L C_L, (\omega_H + \omega_L = 1), \quad (4)$$

in which ω_H and ω_L indicate the weight of the contributions for the two phases. According to Eq. (3) and Eq. (4) we can nicely simulate the experimental data very well as presented in Fig. 4(b) by a solid line. The parameters for the best fit are $\Delta_{0H} = 1.4$ meV, $\omega_H = 0.78$ for $T_{cH} = 9$ K and $\Delta_{0L} = 1.1$ meV, $\omega_L = 0.22$ for $T_{cL} = 6.75$ K and Δ_0 is the gap value at zero temperature. Interestingly, $\omega_H = 0.78$ found here is very close to the relative weight 85% of the high temperature phase which was obtained from the ac susceptibility data in Fig. 4(a). Furthermore, $\Delta_{0L} \sim 1.1$ meV is in good agreement with that from the penetration depth and Andreev reflection experiments[9,11]. These results give a strong evidence that there is no novel pairing symmetry in our alloys.

To get further evidence for this argument, we did similar calculations for the

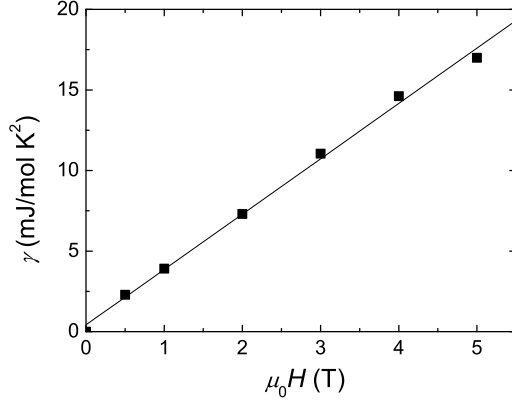


Fig. 5. The electronic specific coefficient $\gamma(H)$ at zero temperature obtained from the calculation based on BCS theory.

specific heat in the mixed state using the same weights of the two phases obtained from the zero field calculation. In the mixed state, there are two different regions, namely the core region and the outside core region. Therefore we adopted a simple two-component model[20,21] which separates the electronic specific heat into two components. The electronic specific heat is thus written as

$$C_e = \alpha \frac{H}{H_{c2}(0)} \gamma_n T + (1 - \alpha \frac{H}{H_{c2}(0)}) C_{es}. \quad (5)$$

Here α is an adjustable parameter. The first part on the right hand side is the quasi-particle density of states (DOS) coming from the normal vortex core regions, and the second part comes from the superconducting regions outside the cores. The results of the quantitative calculations are plotted as solid lines in Fig. 3, and they are in good agreement with the experimental data for all magnetic fields.

In the superconducting state, $C_e = \gamma T$, where γ is the electronic specific heat coefficient that is dependent on temperature and field. According to

Eq. (5), the zero temperature electronic specific heat coefficient $\gamma(H)$ is equal to $\alpha H/H_{c2}(0)\gamma_n$, which is shown in Fig. 5 as solid squares, and the solid line is a linear fit to the data. The obvious linear relationship of γ vs. H presents further evidence that Re_3W is a conventional superconductor in which $\gamma(H)$ is proportional to the number of vortex cores and hence to the applied field. For a nodal superconductor with novel pairing symmetry, on the other hand, a nonlinear $\gamma(H)$ relation should be expected, which is obviously not the case in our present samples[22].

4 Conclusion

In summary, we have synthesized Re_3W alloys by arc melting. From the measurements of ac susceptibility and specific heat on the alloys two distinct superconducting phases were found. Both the qualitative and quantitative analysis were done on the specific heat data in zero field and the mixed state. We found that the simple two-component model based on the BCS theory with an isotropic s -wave gap can fit our experimental data very well, and we obtained a linear $\gamma(H)$ relationship. All these results indicate that the absence of the inversion symmetry does not result in any novel pairing symmetry in Re_3W for both $T_c \sim 7$ K and $T_c \sim 9$ K phases.

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